Quantifying the Tradeoff Between Precaution and Yield in the U.S. Sea Scallop Fishery

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Abstract

Fishery reference points in the U.S. sea scallop fishery are set using yield per recruit analysis. Because of uncertainties in the parameters used in this analysis, the estimated reference points are uncertain. For this reason, it is often argued that target fishing mortality rates should be less than the calculated reference points in order to reduce the risk of overfishing. However, precautionary management also can reduce yield by fishing at suboptimal rates. Here, I use Monte-Carlo simulations to quantify the tradeoff between overfishing risk and loss in yield per recruit. At fishing mortalities near F_{MAX}, the fishing mortality where maximum yield per recruit is obtained, reducing fishing mortality obtains a substantial reduction in the risk of overfishing at little cost of lost yield per recruit. At lower fishing mortality rates, however, the marginal benefit in terms of reduced fishing mortality risk from further reductions in fishing mortality becomes less, and the cost in reduced yield per recruit becomes greater. If implementation uncertainty is added to the analysis, the risk of overfishing as well the loss of yield per recruit is increased, except at F_{MAX}.

Introduction

Fishery reference points are uncertain because the models that generate them depend on parameters that are themselves uncertain. For this reason, it has long been recommended that reference points be set on a precautionary basis, so as to minimize the risk of overfishing. This approach has been codified into U.S. law in 1996 and 2006 by revisions to the Magnuson-Stevens fishery act. However, reducing fishing mortality below F_{MSY} will, by definition, reduce the expected yields that can be obtained from the fishery. While precaution gives benefits in that it reduces the risk of overfishing and its concomitant impacts on the marine ecosystem, it also has a cost in that it reduces expected yield. The purpose of this paper is to explore these tradeoffs in setting reference points for the U.S. sea scallop, *Placopecten magellanicus*, fishery.

Because stock-recruit relationships for sea scallops are not well defined (and are presumably saturated at current and future biomass levels), reference points for sea scallops have been set using yield per recruit analysis, using F_{MAX} as a proxy for F_{MSY}. The most recent sea scallop stock assessment (NEFSC 2007) estimated $F_{\mathrm{MAX}} = 0.24$ on Georges Bank, $F_{\mathrm{MAX}} = 0.36$ in the Mid-Atlantic, and $F_{\mathrm{MAX}} = 0.29$ for the fishery overall.

Uncertainties in yield per recruit analysis can be assessed by estimating a probability distribution for each of the input parameters and then repeatedly drawing parameters at random from these distributions and performing yield per recruit analysis using these choices (Restrepo and Fox 1988). By repeating this procedure a large number of times, the probability distribution of F_{MAX} and the expected yield per recruit at a given fishing mortality can be estimated. From this, the probability of overfishing at a fishing mortality F as well as the loss in yield per recruit incurred by fishing at F rather than F_{MAX} can be calculated.

Besides the uncertainties in the reference points, there is implementation error in that the fishing mortality target intended by managers may not be realized precisely, and the actual fishing mortality may be greater or less than that intended by management. The effect of such errors will also be discussed here.

Methods

Monte-Carlo yield per recruit analysis

A description of basic length-based yield per recruit model used in this analysis can be found in Hart (2003). The yield per recruit calculations depend on a number of parameters which each carry a level of uncertainty:

(1) Von Bertalanffy growth parameters K and L_∞
(2) Shell height/meat weight parameters a and b
(3) Natural mortality rate M
(4) Fishery selectivity parameters α and β
(5) The cull size of the catch and the fraction of discards that survive
(6) The level of incidental fishing mortality, i.e., non-catch mortality caused by fishing.

Each of these parameters were assigned a probability distribution reflecting their level of uncertainty, as discussed below. For each iteration, choices for each of these parameters were drawn from their distributions, and then a yield per recruit analysis was performed. This was repeated for $n = 10000$ iterations for both regions (Georges Bank and Mid-Atlantic) and the results collected. Of particular interest were the expected yield per recruit at a given fishing mortality F and the probability that overfishing would be occurring if fishing mortality was F. The expected yield per recruit was calculated simply as the average of the yield per recruit of each run. The probability of overfishing was estimated as the number of runs for which $F_{\mathrm{MAX}} < F$ divided by the total number of runs.

The estimates of three sets of these parameters (K and L_∞, a and b, and α and β) are confounded, as reflected by a strong correlation between the estimates. For example, a growth curve with a given K and L_∞ resembles one with a slightly smaller K and larger L_∞, implying a negative correlation between the estimates of the two parameters. In these cases, each parameter pair was simulated as correlated normals. In other cases, gamma distributions were used.

The analyses were done separately in each area (Georges Bank and Mid-Atlantic). Expected yields were combined assuming that each area is equally productive. This is approximately correct over the last 25 years, though Georges Bank was more productive over a longer time period, and the Mid-Atlantic more productive in recent years. Calculating the probability of overfishing of the combined resource requires additional assumptions regarding the correlation of parameters in the two regions. It would seem likely that a positive correlation exists, e.g., if the natural mortality estimate of 0.1 was underestimated in one region, it is likely that it is also in the other. For that reason, it is assumed here that the corresponding parameters in the two regions are correlated with a correlation of 1. If this correlation is smaller, the variability between the regions would partially cancel, and the probability of overfishing would be somewhat less than calculated here.

Probability distributions for the simulated parameters

The mean, standard error and correlation (when applicable) for each of the simulated parameters is given in Table 1. These estimates were taken from the latest sea scallop stock assessment (NEFSC 2007) or from the literature. When standard errors were not available, they were estimated using reasonable judgement. Details on each of these parameters is given below.

Growth parameters K and L_∞. These parameters were estimated using a linear mixed-effects model based on the reading of sea scallop rings from shells collected during the 2001-2006 NEFSC sea scallop surveys (NEFSC 2007). These estimates were recently revised by using a slightly refined model and one additional year of data (Hart and Chute 2009). In order to conform to the NEFSC (2007) reference points, the growth parameters estimated there were used, rather than the updated ones. The difference between these is in any case minimal.

As discussed above, K and L_∞ were simulated as negatively correlated normals, with their mean, variance and covariance as estimated in NEFSC (2007). The standard errors of K and L_∞ are very small due to the large amount of data available. The true uncertainty may be greater than this "statistical uncertainty" because of model uncertainties. For example, von Bertalanffy growth appears to well approximate sea scallop growth, but is probably not exactly correct. Such uncertainties are not reflected in the standard errors of the parameters. However, simulations indicate that the mixed-effects model is robust to a number of uncertainties, and likely estimates the mean growth parameters to within 1% of its true value (Hart and Chute 2009).

Shell height/meat weight relationships. Meat weight W at shell height H is calculated using a formula of the form:

$$W = \exp(a + b\ln(H)) \tag{1}$$

The parameters a and b were estimated during the last sea scallop benchmark assessment (NEFSC 2007) using a generalized mixed-effects model (GLMM) based on data collected during the 2001-2006 NEFSC annual sea scallop surveys. This analysis was used to obtain estimates of means, variances, and covariances of the parameters (Table 1). Similar to the growth parameters, the estimates of a and b are somewhat confounded, so that they have a strong negative correlation. This means that the predicted meat weight at a given shell height carries less uncertainty than it would appear from the variances of the individual parameters.

Meat weights vary seasonally, with the greatest meat weights during the late spring and early summer. Meat weights drop considerably after the later summer/early fall spawn and stay low until the spring. These patterns were documented in NEFSC (2007) using observer data. Observers weigh scallop meats in aggregate, so that it is not possible to distinguish which of the shell height/meat weight parameters change seasonally. However, general allometric principles suggest that most of the variation is in the intercept a rather than the slope (or power) parameter b. Haynes (1966) constructed a number of monthly shell height/meat weight relationships, and did not find any significant trend in the slopes. Thus, it was assumed in NEFSC (2007) that all the seasonal variation in meat weights was due to variability in a. If this is the case, seasonality would not affect the F_{MAX} reference point. For this reason, seasonal variability was not considered a source of uncertainty for this analysis.

Natural mortality M. Like most stocks, natural mortality is one of the most uncertain parameters. However, dead "clapper" scallops (dead scallop shells still attached at the hinge) are an indicator of recent natural mortality, due to such causes as disease, high temperatures and sea star predation. The clappers separate some time after death because of hinge degeneration. At equilibrium, the rate of clappers being produced, ML, where L is the number of live scallops, must equal the rate of loss of clappers C/S, where S is the mean clapper separation time and C is the number of clappers. Solving this for M gives:

$$M = \frac{1}{S}\frac{C}{L} \tag{2}$$

so that natural mortality is proportional to the ratio of clappers to live scallops.

Merrill and Posgay (1964) used this idea to estimate natural mortality. They estimated the clapper ratio $C/L = 0.0662$, and the mean separation time $S = 33$ weeks $= 33/52$ years, to estimate an annual natural mortality rate of $(52/33) * 0.0662 = 0.104 \approx 0.1$. Probably the greatest uncertainty in this calculation is the mean separation time S. For example, Dickie (1955) estimated S to be 100 days (14.3 weeks). I assumed S was distributed as a gamma random variable, with mean 33 weeks and standard deviation 15 weeks. The resulting distribution of M has the desirable characteristic of being skewed to the right. This makes sense since, for example, a natural mortality of $M = 0.2$ is possible, but an $M = 0$, or even close to zero, is not. Note that because S appears in the denominator of (2), the mean value of M is not equal to applying equation (2) with the mean value of S, so that the original calculation of Merrill and Posgay (1964) was biased.

Fishery selectivity. Fishery selectivity s was estimated using an ascending logistic curve of the form:

$$s = \frac{1}{1 + \exp(\alpha - \beta H)} \tag{3}$$

where H is shell height. The mean, variances, and correlation of the α and β parameters were estimated based on CASA model runs from the last sea scallop assessment during the most recent time period. Note that fishery selectivity reflects targeting as well as gear selectivity.

Discard mortality. Sea scallops likely tolerate discarding fairly well, provided they are returned to the water relatively promptly and they are not damaged by the capture process or their time on deck. Further uncertainty occurs in the summertime in the Mid-Atlantic, where summer SST exceeds the thermal tolerance of sea scallops. Discard mortality was estimated at 20% in the last assessment, but there is little confidence in this number. Here, discard mortality was simulated as a gamma distribution, with a mean of 0.2 and a standard deviation of 0.15.

Incidental fishing mortality. Incidental fishing mortality occurs when scallops are killed but not captured by the gear. Let F_L be the landed fishing mortality rate and F_I be the rate of incidental fishing mortality. F_I should be proportional to F_L, say $F_I = iF_L$. Based on the studies of Caddy (1973) and Serchuk and Murawski (1989), i was estimated as 0.15 on Georges Bank and 0.04 in the Mid-Atlantic by NEFSC(2007). Because of the considerable uncertainty in these numbers, i was simulated here with a gamma distribution with these means and coefficients of variation of 0.75.

Incorporating management uncertainty

The actual fishing mortality realized may be different than the target fishing mortality set by managers. Thus, for a fixed target fishing mortality F_{TARGET}, the actual fishing mortality F_a is a random variable with density function $p(F)$. Denote by $Y(F)$ the expected yield per recruit obtained by fishing at F, and $Y_t(F)$ the expected yield per recruit obtained by setting the target fishing mortality at F. Note that these will be different, even if the process of setting the management targets is unbiased because yield per recruit curves are non-linear. The expected yield per recruit obtained from setting the target at F_{TARGET} is:

$$Y_t(F_{\text{TARGET}}) = \int_0^\infty p(F)Y(F)\,dF. \tag{4}$$

For these analyses, I assumed that the density function $p(F)$ is normal (in principle, this needs to be truncated at 0, but in practice there is negligible probability that $F < 0$) with mean F_{TARGET} and standard deviation σ. The integral was estimated by discretization with a step size of 0.01.

It remains to estimate the standard deviation σ. The CASA stock assessment model generally estimates fishing mortalities with errors of between 0.01 to 0.02. However, these are estimates of past fishing mortalities, obtained when all the information is available. Managers set effort and/or quota levels based on forecasts that must contain more uncertainty than stock assessment estimates of prior years. The SAMS projection model used for forecasts in the scallop fishery typically gives uncertainty in fishing mortalities of about $\sigma = 0.04$ for short-term forecasts, based on bootstraps of initial conditions and stochastic recruitment variability. This estimate does not include "model error" such as uncertainties in model parameters or changes in fishing practices. If this type of error is of similar magnitude and independent from the stochastic error already quantified by the SAMS model, the total implementation error is about $0.04\sqrt{2} \approx 0.06$. The analysis was conducted both with $\sigma = 0.04$ as a lower bound and $\sigma = 0.06$.

Results and Discussion

The tradeoffs between probability of overfishing and losses in expected yield are shown in Table 2 and Figure 1. Maximal expected yield per recruit are obtained at somewhat higher (by about 0.07) fishing mortalities than calculated in the last sea scallop assessment (NEFSC 2007). There are two reasons for this. First, even though the Merrill and Posgay (1964) estimates were used as the expected value of the clapper ratio and separation time for the clappers, the mean natural mortality was about 0.13, rather than the 0.1 estimated by Merrill and Posgay (1964), due to the uncertainty in the denominator of equation (2). Secondly, the yield per recruit curve is asymmetric, with a greater slope (in absolute magnitude) to the left of F_{MAX} than to the right. As a result, expected yield per recruit will be optimized by fishing at a level slightly greater than the point estimate of F_{MAX}.

Reducing fishing mortality near F_{MAX} produces considerable benefits (in terms of reduced risk of overfishing) at only a small cost (reduced expected yield per recruit). However, as fishing mortality is further reduced, benefits are reduced and costs increase. Basic cost/benefit theory states that the point of optimal cost/benefit will occur where the marginal benefit equals the marginal cost. The difficulty in applying this theory is that costs and benefits are in incommensurate quantities, so that the value of a decreased risk of overfishing compared to a loss in expected yield is subjective. Thus, some judgement is required to decide the appropriate balance. The scallop PDT suggested that the ABC fishing mortality should be set where the risk of overfishing is 0.25, or where the loss of yield per recruit is 1% less than optimal, whichever is less. According to Table 2, this would result in an ABC fishing mortality target of 0.28. While this value is reasonable, arguments can be made for just about any target between 0.2 and 0.3.

Performing similar analyses, but using target fishing mortality instead of actual fishing mortality, indicates that at lower fishing mortalities, implementation error increases both the risk of overfishing and the loss of yield per recruit due to precaution (Tables 3 and 4; Figures 2 and 3).

It is also of interest when setting the target is to calculate the probability of exceeding the ABC fishing mortality, since this triggers "accountability measures." Because implementation error is assumed to be normally distributed, this can be calculated simply from a table of (inverse) normal probabilities (Table 5).

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Table 1. Mean, standard error, and distributions of parameters used in the yield per recruit analysis.

(a) Georges Bank

Parameter	Purpose	Mean	S.E.	Corr.	Distribution
K	Growth	0.375	0.002	-0.6	Corr. Normal
L_∞	Growth	146.5	0.3	-0.6	Corr. Normal
a	SH/MW	-10.70	0.27	-0.998	Corr. Normal
b	SH/MW	2.942	0.055	-0.998	Corr. Normal
S	Nat. mort.	33/52 y	15/52 y		Gamma
α	Selectivity	25.24	8.69	0.998	Corr. Normal
β	Selectivity	0.23	0.08	0.998	Corr. Normal
F_D	Disc. mort.	0.2	0.15		Gamma
i	Incid. mort.	0.15	0.11		Gamma

(b) Mid-Atlantic

Parameter	Purpose	Mean	S.E.	Corr.	Distribution
K	Growth	0.495	0.004	-0.6	Corr. Normal
L_∞	Growth	131.6	0.4	-0.6	Corr. Normal
a	SH/MW	-12.01	0.15	-0.997	Corr. Normal
b	SH/MW	3.22	0.05	-0.997	Corr. Normal
S	Nat. mort.	33/52 y	15/52 y		Gamma
α	Selectivity	21.67	2.77	0.998	Corr. Normal
β	Selectivity	0.214	0.03	0.998	Corr. Normal
F_D	Disc. mort.	0.2	0.15		Gamma
i	Incid. mort.	0.04	0.03		Gamma

Table 2. Probability of overfishing (POF) and loss of yield per recruit (percetage loss compared to maximal) for sea scallops in Georges Bank, the Mid-Atlantic, and overall.

Georges Bank			Mid-Atlantic			Overall		
F	POF	%Loss	F	POF	%Loss	F	POF	%Loss
0.10	0	23	0.20	0.003	7.7	0.15	0	12.33
0.11	0	19.7	0.21	0.007	6.8	0.16	0	10.62
0.12	0	16.7	0.22	0.012	5.9	0.17	0.003	9.13
0.13	0	14.2	0.23	0.021	5.1	0.18	0.005	7.81
0.14	0	12.1	0.24	0.033	4.4	0.19	0.01	6.66
0.15	0.001	10.2	0.25	0.050	3.8	0.20	0.02	5.65
0.16	0.004	8.6	0.26	0.066	3.2	0.21	0.038	4.77
0.17	0.011	7.2	0.27	0.084	2.7	0.22	0.058	4
0.18	0.022	5.9	0.28	0.108	2.3	0.23	0.083	3.32
0.19	0.04	4.9	0.29	0.132	1.9	0.24	0.108	2.74
0.20	0.06	4	0.30	0.159	1.6	0.25	0.13	2.23
0.21	0.087	3.2	0.31	0.186	1.3	0.26	0.158	1.79
0.22	0.119	2.6	0.32	0.215	1.0	0.27	0.189	1.41
0.23	0.154	2	0.33	0.244	0.8	0.28	0.225	1.09
0.24	0.191	1.5	0.34	0.277	0.6	0.29	0.254	0.82
0.25	0.226	1.2	0.35	0.304	0.5	0.30	0.29	0.6
0.26	0.263	0.8	0.36	0.333	0.3	0.31	0.333	0.41
0.27	0.303	0.6	0.37	0.363	0.2	0.32	0.355	0.27
0.28	0.341	0.4	0.38	0.388	0.1	0.33	0.385	0.16
0.29	0.381	0.2	0.39	0.416	0.1	0.34	0.418	0.08
0.30	0.418	0.1	0.40	0.443	0.0	0.35	0.448	0.03
0.31	0.449	0	0.41	0.467	0.0	0.36	0.483	0
0.32	0.484	0	0.42	0.490	0.0	0.37	0.51	0
0.33	0.515	0	0.43	0.512	0.0	0.38	0.535	0.02
0.34	0.54	0	0.44	0.535	0.0	0.39	0.555	0.06
0.35	0.568	0.1	0.45	0.557	0.0	0.40	0.578	0.11

Table 3. Probability of overfishing (POF) and loss of yield per recruit (percetage loss compared to maximal) for sea scallops in Georges Bank, the Mid-Atlantic, and overall, with respect to target fishing mortality rates, assuming $\sigma = 0.04$ implementation uncertainty.

Georges Bank			Mid-Atlantic			Overall		
F_{TARGET}	POF	%Loss	F_{TARGET}	POF	%Loss	F_{TARGET}	POF	%Loss
0.10	0.001	27.7	0.20	0.015	8.7	0.15	0.016	14.06
0.11	0.002	23.6	0.21	0.022	7.6	0.16	0.022	12.12
0.12	0.004	20.0	0.22	0.030	6.6	0.17	0.029	10.43
0.13	0.007	17.0	0.23	0.040	5.8	0.18	0.038	8.96
0.14	0.012	14.4	0.24	0.052	5.0	0.19	0.049	7.66
0.15	0.018	12.2	0.25	0.067	4.3	0.20	0.062	6.51
0.16	0.027	10.3	0.26	0.083	3.7	0.21	0.076	5.50
0.17	0.038	8.7	0.27	0.102	3.2	0.22	0.093	4.63
0.18	0.053	7.3	0.28	0.122	2.7	0.23	0.111	3.86
0.19	0.070	6.1	0.29	0.145	2.3	0.24	0.131	3.20
0.20	0.091	5.0	0.30	0.169	1.9	0.25	0.153	2.62
0.21	0.114	4.1	0.31	0.194	1.6	0.26	0.177	2.12
0.22	0.141	3.4	0.32	0.220	1.3	0.27	0.201	1.69
0.23	0.170	2.7	0.33	0.247	1.1	0.28	0.227	1.33
0.24	0.201	2.2	0.34	0.275	0.9	0.29	0.254	1.02
0.25	0.234	1.7	0.35	0.302	0.7	0.30	0.281	0.76
0.26	0.268	1.3	0.36	0.330	0.5	0.31	0.309	0.55
0.27	0.303	1.0	0.37	0.357	0.4	0.32	0.337	0.37
0.28	0.337	0.8	0.38	0.384	0.3	0.33	0.364	0.24
0.29	0.372	0.6	0.39	0.410	0.2	0.34	0.392	0.14
0.30	0.406	0.4	0.40	0.435	0.2	0.35	0.419	0.06
0.31	0.439	0.3	0.41	0.460	0.1	0.36	0.445	0.02
0.32	0.471	0.3	0.42	0.484	0.1	0.37	0.470	0.00
0.33	0.501	0.2	0.43	0.507	0.1	0.38	0.495	0.00
0.34	0.530	0.2	0.44	0.529	0.0	0.39	0.518	0.03
0.35	0.558	0.3	0.45	0.551	0.0	0.40	0.541	0.07

Table 4. Probability of overfishing (POF) and loss of yield per recruit (percetage loss compared to maximal) for sea scallops in Georges Bank, the Mid-Atlantic, and overall, with respect to target fishing mortality rates, assuming $\sigma = 0.06$ implementation uncertainty.

Georges Bank			Mid-Atlantic			Overall		
F_{TARGET}	POF	%Loss	F_{TARGET}	POF	%Loss	F_{TARGET}	POF	%Loss
0.1	0.006	27.5	0.2	0.033	9.4	0.15	0.016	16.22
0.11	0.009	25.2	0.21	0.042	8.2	0.16	0.022	13.71
0.12	0.014	22.9	0.22	0.053	7.2	0.17	0.029	11.77
0.13	0.019	20.5	0.23	0.064	6.3	0.18	0.038	10.09
0.14	0.026	19.4	0.24	0.078	5.4	0.19	0.049	8.63
0.15	0.034	16.7	0.25	0.093	4.7	0.2	0.062	7.36
0.16	0.044	14.1	0.26	0.110	4.1	0.21	0.076	6.25
0.17	0.057	11.9	0.27	0.129	3.5	0.22	0.093	5.28
0.18	0.071	10.1	0.28	0.149	3.0	0.23	0.111	4.42
0.19	0.088	8.5	0.29	0.170	2.5	0.24	0.131	3.67
0.2	0.107	7.1	0.3	0.192	2.2	0.25	0.153	3.03
0.21	0.128	5.9	0.31	0.216	1.8	0.26	0.177	2.47
0.22	0.151	4.9	0.32	0.240	1.5	0.27	0.201	1.99
0.23	0.176	4.1	0.33	0.265	1.3	0.28	0.227	1.58
0.24	0.202	3.3	0.34	0.290	1.0	0.29	0.254	1.23
0.25	0.231	2.7	0.35	0.316	0.9	0.3	0.281	0.93
0.26	0.260	2.2	0.36	0.341	0.7	0.31	0.309	0.68
0.27	0.291	1.8	0.37	0.367	0.6	0.32	0.337	0.48
0.28	0.321	1.4	0.38	0.392	0.4	0.33	0.365	0.32
0.29	0.353	1.2	0.39	0.417	0.3	0.34	0.392	0.20
0.3	0.384	0.9	0.4	0.441	0.3	0.35	0.419	0.11
0.31	0.415	0.8	0.41	0.465	0.2	0.36	0.445	0.05
0.32	0.445	0.6	0.42	0.489	0.2	0.37	0.470	0.01
0.33	0.475	0.5	0.43	0.511	0.1	0.38	0.495	0.00
0.34	0.504	0.4	0.44	0.533	0.1	0.39	0.519	0.01
0.35	0.532	0.4	0.45	0.554	0.1	0.4	0.541	0.04

Table 5. Risk of exceeding the ABC and hence encountering accountability measures at various reductions in target fishing mortalities below the ABC fishing mortality.

Reduction in F	$P(F > F_{\text{ABC}})$ $\sigma = 0.04$	$P(F > F_{\text{ABC}})$ $\sigma = 0.06$
0.01	0.401	0.434
0.02	0.309	0.369
0.03	0.227	0.309
0.04	0.159	0.252
0.05	0.106	0.202
0.06	0.067	0.159
0.07	0.040	0.122
0.08	0.023	0.091
0.09	0.012	0.067
0.10	0.006	0.048
0.11	0.003	0.033
0.12	0.001	0.023

Figure legends

Figure 1. The probability of overfishing (solid) and loss in yield per recruit (dashed) for (a) Georges Bank, (b) Mid-Atlantic and (c) overall, as a function of true fishing mortality.

Figure 2. Figure 1. The probability of overfishing (solid) and loss in yield per recruit (dashed) for (a) Georges Bank, (b) Mid-Atlantic and (c) overall, as a function of target fishing mortality with implementation error $\sigma = 0.04$.

Figure 3. The probability of overfishing (solid) and loss in yield per recruit (dashed) for (a) Georges Bank, (b) Mid-Atlantic and (c) overall, as a function of target fishing mortality with implementation error $\sigma = 0.06$.

Figure 1

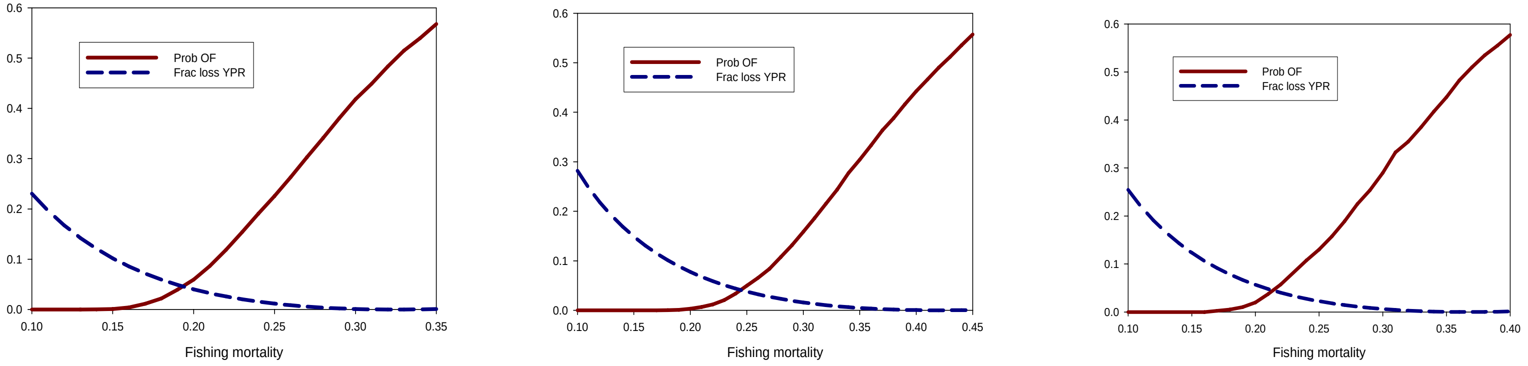

(a) (b) (c)

Figure 2

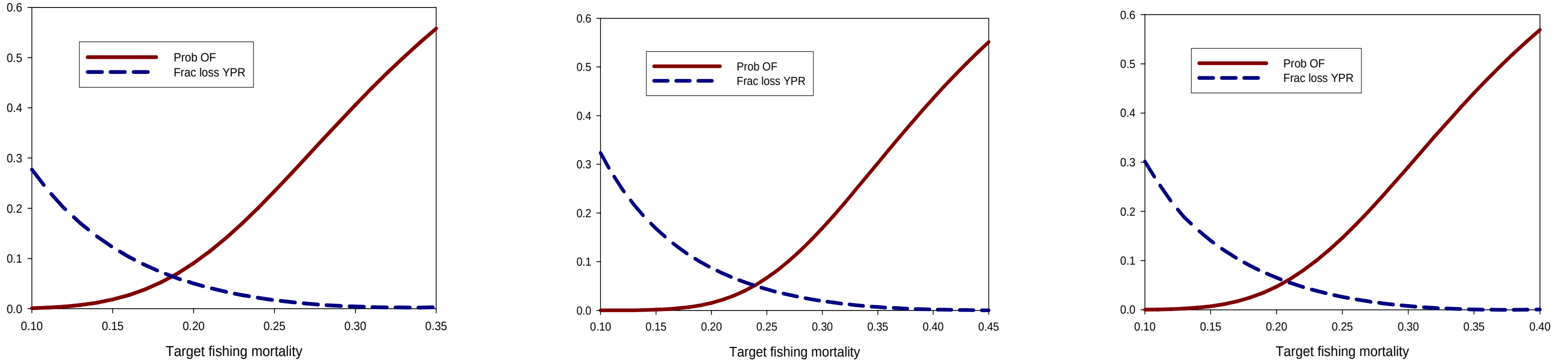
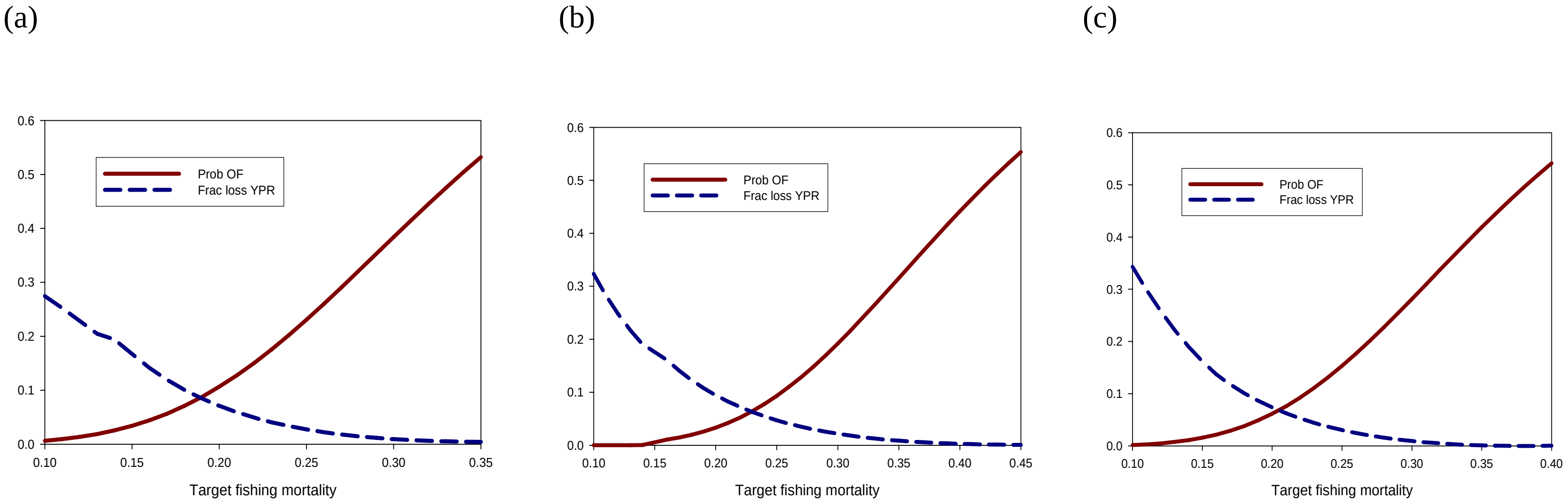

(a) (b) (c)

Figure 3


(a)
(b)
(c)
Prob OF
Frac loss YPR
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
Target fishing mortality